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Citation: *AIP Advances* **5**, 127142 (2015); doi: 10.1063/1.4939582

View online: <http://dx.doi.org/10.1063/1.4939582>

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## Polarization rotator of arbitrary angle based on simple slot-array

Xiaoming Liu,<sup>1,a</sup> Xiaohang Cao,<sup>1</sup> Junsheng Yu,<sup>1</sup> Xiaodong Chen,<sup>2</sup>  
 Yuan Yao,<sup>1</sup> Limei Qi,<sup>1</sup> Zhijiao Chen,<sup>1</sup> and Jun Zhou<sup>3</sup>

<sup>1</sup>*School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing, 100876, China*

<sup>2</sup>*School of Electronic Engineering and Computer Science, Queen Mary, University of London, London E1 4NS, United Kingdom*

<sup>3</sup>*School of Physical Electronics, University of Electronic Science and Technology of China, Chengdu, 610054, China*

(Received 26 November 2015; accepted 22 December 2015; published online 31 December 2015)

A novel polarization rotator of arbitrary angle was proposed and realized based on simple slot arrays. To achieve the rotation of an arbitrary angle  $\alpha$ , the slots on the first layer have to be at an angle of  $\alpha$  to the slots on the second layer. Consequently, 90° rotation can be realized using two perpendicularly oriented slot arrays, which overturns the conventional notion of that perpendicular slot arrays are not possible to pass electromagnetic wave. In addition, such structure provides the same bandwidth comparing to its counterpart utilized for frequency selective surface (FSS). Furthermore, such structure is much easier to be fabricated compared to the substrate integrated waveguide (SIW) array. Moreover, low insertion loss can be achieved based on metallic material. © 2015 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). [<http://dx.doi.org/10.1063/1.4939582>]

### I. INTRODUCTION

Quasi-optical (QO) system has been widely employed in many radio astronomy telescopes,<sup>1</sup> deep-space detection missions,<sup>2</sup> and remote sensing polarimetric imaging or radiometers.<sup>3–5</sup> In these QO systems, polarization rotation components are usually required to achieve multi-polarization receiving or polarization separation. For instance, Faraday rotator in combination with wire grid is employed to realize high-performance QO isolators and circulators.<sup>6</sup>

A polarization rotator is a passive device that can rotate the electric field of an incident electromagnetic wave by a certain degree.<sup>7</sup> Many techniques can be found to realize polarization rotation, such as waveguide polarization rotator,<sup>8</sup> wire-grid polarizer and a plane mirror with quarter-wave spacing,<sup>9</sup> Faraday rotation modulators,<sup>10</sup> and periodic structures.<sup>7,11,12</sup> Waveguide polarization rotator is suitable for guided-wave system. A QO system, however, is working in free space transmission manner. The wire-grid polarizers are not suitable for high-power systems. Faraday rotation modulators are probably the most pervasive component. Unfortunately, insertion loss is the main drawback of the Faraday rotation modulator. To achieve an insertion loss of 0.5-1.3 dB Faraday rotator, very complicated structure may be needed.<sup>13</sup>

In recent years, periodic structure based polarization rotators have been extensively investigated, with versatile unit cells developed for use as spatial filter, which are normally referred to as frequency selective surfaces (FSSs).<sup>14–16</sup> Examples are chiral structures,<sup>12,17</sup> and meander lines printed on a substrate with multi-layer structure.<sup>11</sup> With the emergency of metamaterial concept, polarization rotator based on cascaded metallic patterns or their complementary counterparts have been widely investigated.<sup>18–20</sup> These patterns are printed on dielectric substrate, being not suitable

<sup>a</sup>Email: [xiaoming\\_liu@bupt.edu.cn](mailto:xiaoming_liu@bupt.edu.cn)

for high-power radar application. Very recently, substrate integrated waveguide (SIW) is reported in the application of polarization rotation.<sup>7,21</sup> The SIW has been widely employed in many areas, including 3D FSS,<sup>22,23</sup> antenna and so forth.<sup>24–26</sup> The SIW based components normally present low-cost, low-loss properties with broader bandwidth, and high quality factor.<sup>25</sup> The SIW based FSS usually exhibits sharp roll-off at the transition band.<sup>26</sup> In a SIW structure, the unit cell is surrounded by a number of conducting pins, forming a cavity, which can support many waveguide modes. A 90° rotator can be achieved due to mode coupling, such as the coupling between TM<sub>120</sub> and TM<sub>210</sub> modes. Nevertheless, SIW structures are in comparison much more complicated than a normal periodic structure. For instance, the surrounding pins are obstacles to fabrication, especially in sub-millimeter wave and THz wave range, where the half-wave length is smaller than 1 mm. Squeezing too many pins in such a small dimension inevitably requires very high precision fabrication scheme. In addition, such structure is not applicable to cases where arbitrary rotation is required.

As a matter of fact, the surrounding pins are not necessary to achieve polarization rotation. In this paper, it will be reported that polarization rotation of arbitrary angle can be realized based on simple slot array. A rotation of 90° can be easily realized with two perpendicularly oriented slot arrays, which overturns the preconceived notion of that it is impossible for electromagnetic waves to pass through two perpendicularly oriented slot arrays.

## II. DESIGN AND SIMULATION

For a conventional multi-layer slot array FSS, the orientation of the slot of each layer is identical to each other, as illustrated in Fig. 1(a), where both the first and the second layers are horizontally-oriented slot arrays. In this case, only the vertically polarized electromagnetic wave (in this case the  $E_y$  component) is possible to pass through this structure. The horizontally oriented polarization component is rejected. Generally speaking, the length of each slot is approximately half wavelength of its first order resonant frequency, as determined by

$$f = \frac{c}{2l\sqrt{\epsilon_r}}, \quad (1)$$

where  $l$  is the length of the slot.

An SIW based structure of both frequency selective and polarization rotation properties are illustrated in Fig. 1(a). Such structure can be utilized for 90° and 45° rotations. For instance, the first layer in Fig. 1(a) is an array of horizontal slot, with a number of shorting pins distributed on the

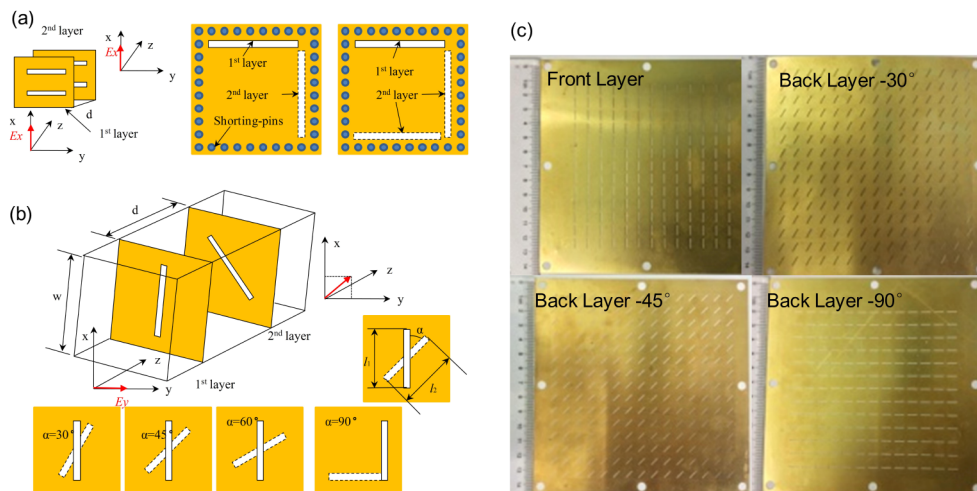


FIG. 1. Periodic structures. (a) A two layer slot array FSS and the unit cell of a SIW structure; (b) Unit cell of arbitrary angle of polarization rotation, and (c) Fabricated prototypes.

periphery of the unit cell. The shorting pins are in this structure employed to form a waveguide cavity. Vertically polarized wave passes through the first layer, forming TM<sub>mn</sub>0 mode on the incident surface. Through mode coupling, a TM<sub>nm</sub>0 mode may be formed, letting it pass through the second layer, and in this way polarization rotation can be realized. A 45° rotation may be achieved through cutting two orthogonal slots on the second layer to form a dual-mode configuration.<sup>7</sup>

Such structure is actually a coupling waveguide array, and therefore can support TM<sub>mn</sub>0 modes with  $m > 0$ ,  $n > 0$ . An ideal mode choice may be TM<sub>12</sub>0 and TM<sub>21</sub>0 modes, as explained in Ref. 21. TM<sub>11</sub>0 mode also works in such a structure as a polarization rotator, however, exhibits narrow pass-band comparing to the dual-mode case, see Fig. 5(a) in Ref. 21. The resonant frequency of TM<sub>mn</sub>0 mode can be determined by

$$f_{TM_{mn}0} = \frac{c}{2\sqrt{\epsilon_r}} \sqrt{\left(\frac{m}{W_{eff}}\right)^2 + \left(\frac{n}{L_{eff}}\right)^2}, \quad (2)$$

where  $\epsilon_r$  is the relative permittivity of the dielectric in the cavity,  $W_{eff}$  and  $L_{eff}$  are the effective width and length of the cavity respectively.

In addition, to achieve best transmission performance, the slots are located near the edge of the SWI cavity. They can also be located in the center of the cavity, however, exhibits higher transmission leakage of the undesired polarization.<sup>21</sup> Actually, the presence of shorting pins complicates the fabrication, particularly in the sub-millimeter wave and THz wave range. Moreover, the SIW structure is difficult to realize rotation of arbitrary angle due to its limited supporting modes. It is demonstrated latter that only one slanted slot array is required to achieve arbitrary angle of rotation.

The unit cell based on simple structure of slot array is illustrated in Fig. 1(b), where the first layer is a vertical slot array, and the second layer is a slanted one at an angle of  $\alpha$  to the first array. By properly optimization of pertinent parameters, the lengths of the slots,  $l_1$  and  $l_2$ , the size of the unit cell  $w$ , and the distance  $d$  between the two layers, satisfactory results can be obtained. It has to be mentioned that, such a structure is inspired from the SIW structure, though the working principles are not quite the same. For instance, for the 90° rotation, the structure proposed in this paper is the same as that in a SIW structure. However, for other angle of rotation, only a slanted slot is required on the second layer.

Parameters for the prototypes are shown in Table I. It is seen that the length of the slot is around  $6.5 \pm 0.4$  mm, approximately half-wavelength at 22 GHz. The simulated results are shown in Fig. 2, where (a) and (b) are 30° and 90° rotations respectively. Other cases are not shown due to the limitation of space.

From Figs. 2(a) and 2(b), it is clearly seen that both the  $S_{21}(E_y \Rightarrow E_y)$  and  $S_{21}(E_y \Rightarrow E_x)$  have a bandwidth of roughly 1 GHz, being centered at 22 GHz. Fig. 2(a) demonstrates that  $S_{21}(E_y \Rightarrow E_y)$  is around -1.42 dB within its bandwidth, while  $S_{21}(E_y \Rightarrow E_x)$  is near -6.2 dB. It is seen from Fig. 3(b),  $S_{21}(E_y \Rightarrow E_x)$  is around -0.2 dB, showing a high coupling from y-polarization to x-polarization. Since a linearly polarized wave can be written as

$$\vec{E} = E_x \hat{x} + E_y \hat{y}. \quad (3)$$

It can be found that these simulated results are in line with Eq. (3) within a very low transmission loss, less than 0.3 dB.

To experimentally verify this concept, three prototypes were fabricated and measured, as shown in Fig. 1(c). Prototypes are designed to be working at 22 GHz. Each layer is made of copper with

TABLE I. The parameters of the four configurations in Fig. 1(b), unit for length dimension is in mm.

(mm)	$\alpha = 30^\circ$	$\alpha = 45^\circ$	$\alpha = 60^\circ$	$\alpha = 90^\circ$
$W$	9	8.8	7.7	9
$d$	11.6	12.4	12.6	0.6
$l_1$	6.4	6.4	6.1	6.9
$l_2$	6.5	6.3	6.3	6.9

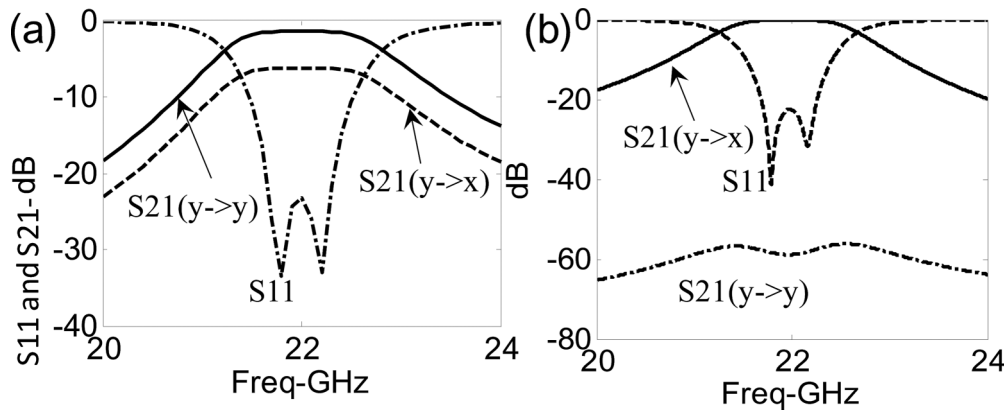


FIG. 2. Simulated results for polarization rotation. (a) 30° rotation S21 and S11, (b) 90° rotation S21 and S11.

slots fabricated by etching technique. The fabrication accuracy is within 0.02 mm. Since the slot width is 0.5 mm, and the slot length is more than 6.0 mm, such fabrication accuracy is acceptable. Free space technique was employed to measure the S parameters of each prototype, where two focusing-lens antennas are connected to a Vector Network Analyzer (VNA). The fabricated prototypes were placed at the beam waist between the transmitting and receiving antennas with absorbers mounted on the periphery. A reference measurement of open air transmission was conducted to normalize the signal level. The transmission characteristic was measured for each prototype. To reduce the multi-reflection effect, time gating technique can be applied.

### III. EXPERIMENTAL RESULTS

The measured results are presented in Fig. 3 in comparison with the simulated ones. The case of 60° rotation is not fabricated since it is a complimentary case to 30° rotation. Overall, the measured results are in good agreement with the simulated ones. Taking 30° rotation as an example, the operating band is between 21.4-22.4 GHz, comparing to 21.5-22.5 GHz by simulation. The difference of  $S_{21}(E_y \Rightarrow E_y)$  between measurement and simulation is within 0.2 dB. The reflection coefficients  $S_{11}$  are higher than simulation, but all below -13 dB in the pass band. Similar observations can be made for the cases of 45°, and 90° rotations. The measured results of  $S_{11}$  and calculated insertion loss (IL) in tabulated in Table II.

It is clearly demonstrated that the structure presented in Fig. 1(b) can be designed for polarization rotation of arbitrary angle, as well as for use of frequency selection with very low insertion loss. In essence, the conventional two-layer FSS is a special case with  $\alpha = 0$ . Therefore, such structure provides one with the same bandwidth no matter what the value of  $\alpha$  is. Normally, two transmission

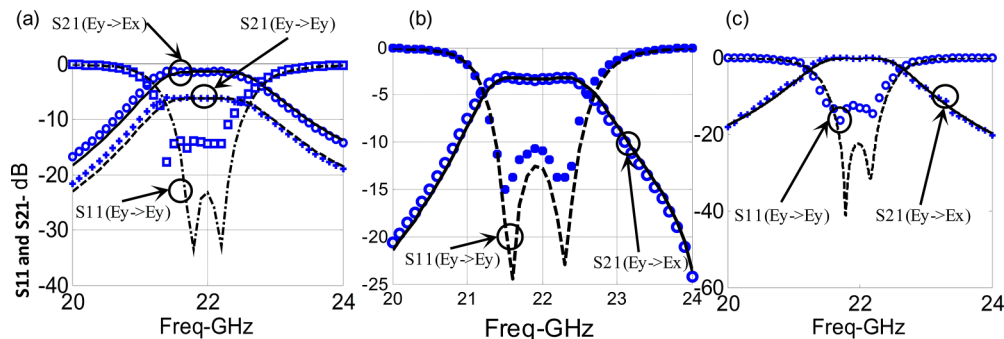


FIG. 3. Measured results in comparison with simulated ones.

TABLE II. Measured results of S21 and insertion loss (IL) in dB, Frequency in GHz.

Type	Frequency	21.40	21.70	21.90	22.10	22.40
30°	Ey->Ey	-1.32	-1.40	-1.41	-1.41	-1.80
	Ey->Ex	-6.10	-6.20	-6.19	-6.18	-6.80
	IL	-0.07	-0.16	-0.16	-0.16	-0.61
45°	Ey->Ey	-3.34	-3.25	-3.38	-3.30	-3.26
	Ey->Ex	-3.35	-3.25	-3.38	-3.21	-3.26
	IL	-0.34	-0.24	-0.37	-0.25	-0.25
90°	Ey->Ey	-	-	-	-	-
	Ey->Ex	-0.66	-0.10	-0.25	-0.20	-0.45
	IL	-0.66	-0.10	-0.25	-0.20	-0.45

poles can be observed, as presented in Fig. 2. A two-layer structure normally provides one with an extra resonant frequency due to coupling effect. Therefore, wider bandwidth can be obtained with steeper roll-off.

In a general case, the loss tangent has to be on the order of  $10^{-3}$  to maintain low dielectric loss. In contrast, no dielectric substrate is actually needed for metallic slot array. Consequently, low insertion loss can be achieved.

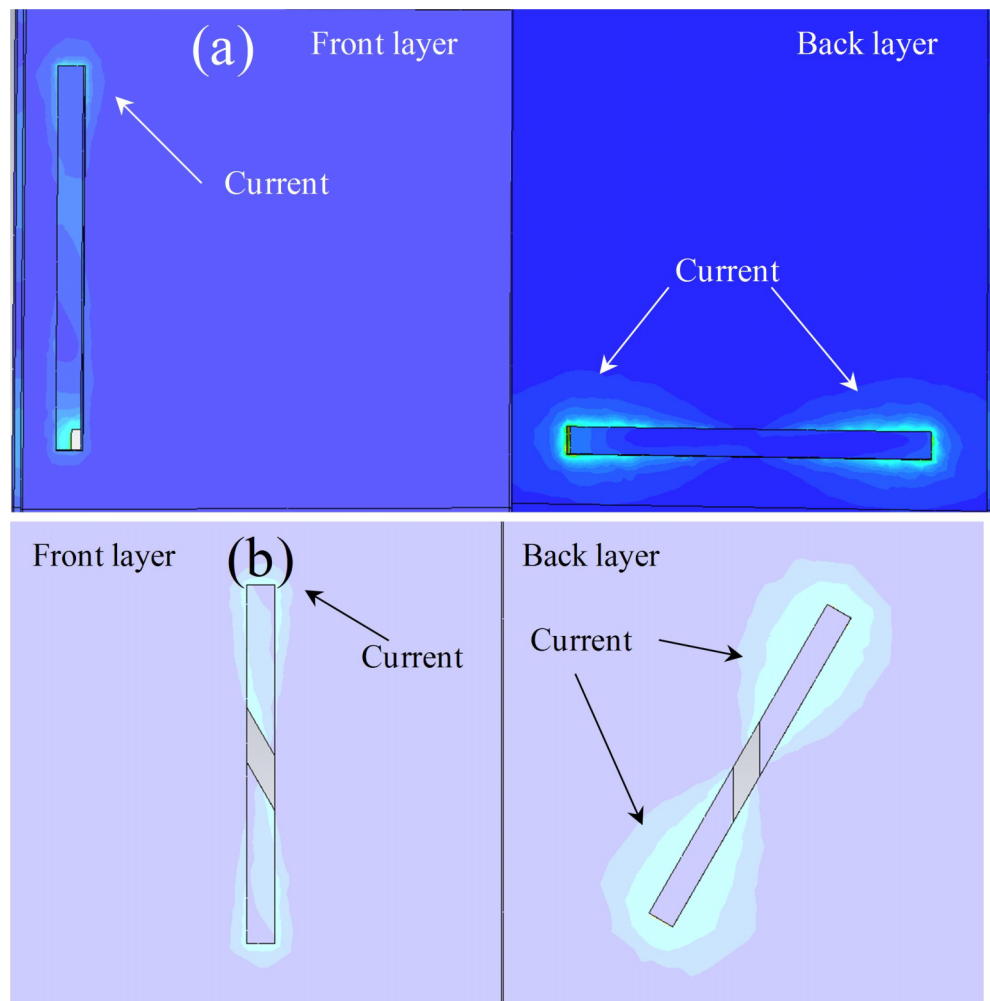


FIG. 4. Current distribution of the rotators. (a) 90° rotator; (b) 30° rotator.



Generally speaking, ISW structure is explained using mode coupling theory in a waveguide cavity. The unit cell of an ISW periodic structure can be modeled as an aperture-waveguide-aperture structure, which is a filter structure.<sup>21</sup> Therefore, the coupling from the input mode to the output mode can be explained through reduced mode theory. In comparison, the structure in Fig. 1(b) is more relied on surface current induction, abided by Floquet mode and boundary conditions. Taking 90° rotator as an example, as illustrated in Fig. 4(a), the maximal current occurs at the ends of each slot. This is due to the transmission line theory that a slot can be modeled as a shorted circuit line. Therefore, coupling effect is easily to take place when the slots on the first and second layers are placed end by end. The electric field is perpendicular to the slot, and consequently the output field rotated from  $E_y$  to  $E_x$ , i.e. 90° rotation is achieved.

The current distribution is demonstrated in Fig. 4, predicted by CST Microwave Studio. It is clearly shown that, on the front layer (entry layer), the current resembles a short circuited half-wavelength resonance distribution along the vertical slot, while on the back layer (the output layer), the current distribution is a first order resonant along the output slot. Such kind of current distribution is a typical distribution of slot antenna, the radiation E-plane of which is perpendicular to the slot. Subsequently, the output electric field of such structure is perpendicular to the output slot, resulting in polarization rotation.

## ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support of the National Natural Science Foundation of China under the contract numbers of 61401031, 61505022, 61474112, and Beijing Higher Education Young Elite Teacher Project (Grant No.YETP0438). The authors would also like to thank Keysight Technology (Agilent) for providing measurement support.

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